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A review for research and new design options of solar absorption cooling systems

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ABSTRACT

Solar cooling technology is environmentally friendly and contributes to a significant decrease of the CO_2 emissions which cause the green house effect. Currently, most of the solar cooling systems commonly used are the hot water driven lithium bromide absorption chillers. According to the operating temperature range of driving thermal source, single-effect $LiBr/H_2O$ absorption chillers have the advantage of being powered by ordinary flat-plate or evacuated tubular solar collectors available in the market. In this paper, besides the review of the existing theoretical and experimental investigations of solar single-effect absorption cooling systems, some new design options with regard to solar collectors, auxiliary energy systems and cooling modes were introduced. And then, other main types of solar absorption cooling systems based on double-effect, half-effect and two-stage absorption chillers were summarized. For buildings with high amounts of cooling load and limited installation area, solar-powered double-effect absorption cooling systems may be considered on condition that the direct irradiation is high enough. Half-effect absorption chillers and two-stage absorption chillers seem to be more suitable for air-cooled solar absorption cooling systems in hot and dry regions which are short of water. It is highly recommended to study the standardised design guidelines according to different areas for the purpose of widespread applications of solar cooling systems.

Contents

1. Introduction

In recent years, more and more attention has been paid on the application potential of solar cooling for buildings. Solar cooling technology appears to be a promising alternative to the conventional electrical driven units. The main advantages of solar cooling systems concern the reduction of peak loads for electricity utilities, the use of zero ozone depletion impact refrigerants, the decreased primary energy consumption and decreased global warming impact [1,2].

The current technologies in the market for cooling production, using solar thermal energy are: absorption machines, solid and

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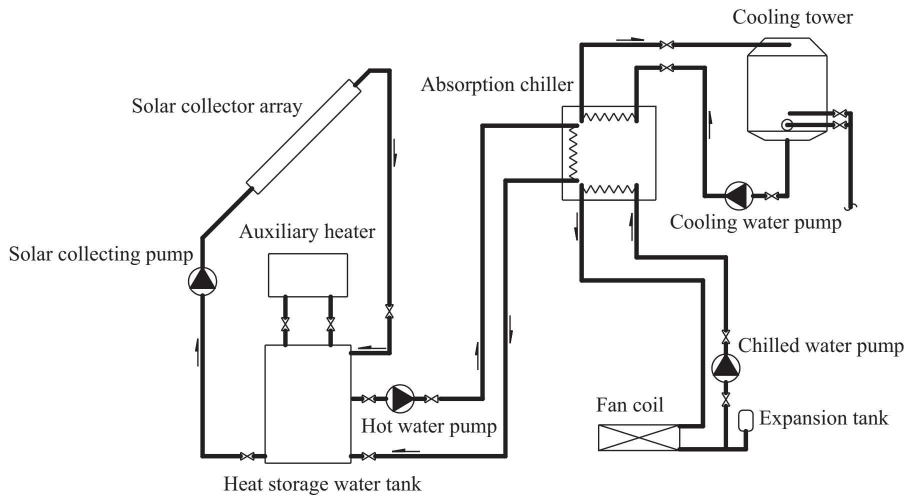

Fig. 1. General scheme of a solar-powered single-effect absorption cooling system.

liquid desiccant and solid adsorption. Cold production through absorption cycles has been traditionally considered one of the most desirable applications for solar thermal energy. So, the most commercially developed solar cooling technologies are the absorption systems [3]. The applications and feasibility of such systems in different areas were also been reported. It was counted that about 59% of the solar cooling systems in Europe were solar absorption cooling systems [3,4]. In China, almost all the large-scale solar cooling demonstration projects during the last twenty years were based upon absorption systems. As for tropical areas, the solar intensity is very high and thus solar energy can be used as power sources. Jaruwongwittaya et al. [5] pointed that the absorption cooling technology using lithium bromide/water was the most appropriate for the solar applications in Thailand. Fong et al. [6] compared five types of solar cooling systems for Hong Kong, which is commonly featured with long hot and humid summer. The solar cooling systems included the solar electric compression refrigeration, solar mechanical compression refrigeration, solar absorption refrigeration, solar adsorption refrigeration and solar solid desiccant cooling. Through this comparative study, it was found that solar electric compression refrigeration and solar absorption refrigeration had the highest energy saving potential in Hong Kong. The former is to make use of the solar electric gain, while the latter is to adopt the solar thermal gain. These two solar cooling systems would have even better performances through the continual advancement of the solar collectors. It will provide a promising application potential of solar cooling for buildings in the subtropical region.

Commercially available absorption chillers for air conditioning applications usually operate with solution of lithium bromide in water and use steam or hot water as the heat source [7]. It has been testified that single-effect LiBr/H_2O absorption units using fossil-fuels are not competitive from the energy, economic and environmental points of view. They are only competitive when using waste or renewable heat as part of the driving energy [8]. Besides, according to the operating temperature range of driving thermal source, single-effect LiBr/H_2O absorption chillers have the advantage of being powered by ordinary flat-plate or evacuated tubular solar collectors available in the market. Consequently, the majority of solar cooling systems are based on single-effect LiBr/H_2O absorption chillers. Under normal operation conditions, such machines need typically temperatures of the driving heat of 80–100 °C and achieve a COP of about 0.7. Fig. 1 illustrates a general scheme of a solar-powered single-effect absorption cooling system. The system employs a solar collector array, an absorption chiller, a cooling tower, a heat storage water tank and an auxiliary heater. The hot water storage tank is used in the system as a heat reservoir. When there is no cooling demand to satisfy, the solar energy is accumulated in the storage tank. When solar energy is insufficient to heat the water to the required generator inlet temperature level, the auxiliary heat source is provided to supply the generator.

Besides single-effect absorption chillers, double-effect absorption chillers are also available in the market. Different from the former, two generators working at different temperatures are operated in series, whereby the condenser heat of the refrigerant desorbed from the first generator is used to heat the second generator. Thereby a higher COP in the range of 1.1–1.2 is achieved. However, driving temperatures in the range of 140–160 °C are typically required to drive those chillers [3]. Consequently, high-temperature solar collectors such as parabolic trough solar collectors should be chosen in solar cooling systems based on double-effect absorption chillers.

As for other types of absorption chillers, there are only a few theoretical research works about half-effect absorption chillers and two-stage absorption chillers powered by solar energy. However, the practical applications of such systems were hardly any reported.

In this paper, the research works of solar-powered single-effect absorption cooling systems as well as other main types of solar absorption cooling systems were reviewed. Some new design options were summarized mainly based upon solar-powered single-effect absorption cooling systems. And then, some suggestions about the design of solar cooling systems were given.

2. Solar-powered single-effect absorption cooling systems

2.1. Experimental investigations

Although there were some solar absorption cooling systems in large capacities up to several hundred kilowatts, the experimental investigations were mainly based upon medium and small-sized solar cooling systems. Usually, the cooling capacity and COP (coefficient of performance) of solar cooling systems were tested under practical operating conditions.

Rosiek and Batlles [9] reported the solar-powered single-effect absorption cooling system installed in the Solar Energy Research Center of Spain. According to the calculation, the heating and cooling demand during the whole year were 8124 kWh and 13,255 kWh, respectively. The flat-plate solar collectors with the area of 160 m^2 were used to meet the energy demands either for heating in winter or cooling in summer. For covering the cooling

Table 1
Main operating parameters of the existing solar-powered single-effect absorption cooling systems.

Operating temperature/°C			COP	Solar collecting efficiency
Hot water	Chilled water	Cooling water		
65–100	7–15	26–32	0.33–0.70	35%–50%

demand, a single-effect absorption chiller with the cooling capacity of 70 kW was chosen. The performance of the solar-powered cooling system was monitored and controlled by a control and data-acquisition system. During one year of operation, it could be seen that the solar collectors were able to provide sufficient energy to supply the absorption chiller during the summer mode and sufficient to cover the whole heating demand. The average values of COP and the cooling capacity were calculated for summer months, obtaining values of the order of 0.6 and 40 kW, respectively.

Ortiz et al. [10] and Mammoli et al. [11] carried out the experiments of a solar cooling system for a 7000 m^2 educational building situated in a high-desert climate. There were two kinds of solar collectors in this system, which included 124 m^2 of flat-plate collectors and 108 m^2 of vacuum tubular collectors. A water–glycol mixture was pumped through the arrays and through a heat exchanger, which was connected to a hot water storage tank with approximately 34 m^3 useful volume. The absorption chiller was a Yazaki single-effect LiBr/H_2O water fired chiller. This 70 kW absorption chiller was designed to work with hot water supply temperatures in the range from 70 to 95 °C. The cold water produced by the absorption chiller could be stored in seven 50 m^3 cold water tanks or directly supplied to the air handling units cooling coils. Large chilled water storage tanks were charged off-peak and discharged during the day, cooling the building in parallel with the chiller. Both the hot and cold water storage used thermal stratification. If the system could not produce enough heating or cooling in standalone mode, connections to campus chilled water and steam could be activated to assist cooling and heating. According to the experimental results, in the peak of summer, the solar cooling system could supply approximately 18% of the total cooling load. This percentage could be increased to 36% by tuning the air handler operation and by improving the insulation in the storage tank.

Syed et al. [12] investigated a solar cooling system consisting of a 35 kW LiBr/H_2O absorption machine energized by 49.9 m^2 of flat-plate collectors. Thermal energy was stored in a 2 m^3 stratified hot water storage tank during hours of bright sunshine. The generator design of the machine allowed the use of hot water in the temperature range of 65–90 °C. The measured maximum instantaneous, daily average and period average COP were 0.60 (at maximum capacity), 0.42 and 0.34, respectively. The daily average collector efficiency (without considering pipe and plate heat exchanger losses) was 50%. Through the analysis of energy flows in the system, it was demonstrated that the technology worked best in dry and hot climatic conditions where large daily variations in relative humidity and dry bulb temperature prevailed.

Praene et al. [13] presented a solar-powered 30 kW LiBr/H_2O single-effect absorption cooling system which was designed and installed at Institut Universitaire Technologique of Saint Pierre. It was reported that the solar loop could produce hot water to fire the absorption chiller from 8:00 AM to 5:00 PM. According to the first field test, the system was sufficient to obtain thermal comfort with the mean air temperature inside the classrooms of about 25 °C.

Li and Sumathy [14] studied the performance of a solar-powered absorption air conditioning system with a partitioned hot water storage tank. The system employed a flat-plate collector array with the surface area of 38 m^2 to drive a LiBr/H_2O absorption chiller of 4.7 kW cooling capacity. The system was provided with a storage tank (2.75 m^3) which was partitioned into two parts. The upper part had a volume of about one-fourth of the entire tank. The performance of this modified system was presented and compared with the conventional system design (whole-tank mode). The study revealed that the solar cooling effect could be realized nearly 2 h earlier for the system operating in partitioned mode. In this system a solar COP of about 0.07, which was about 15% higher than with traditional whole-tank mode, was attained. Experimental results also showed that during cloudy days, the system could not provide a cooling effect, when operated conventionally, however in the partitioned mode-driven system the chiller could be energized, using solar energy as the only heat source.

Agyenim et al. [15] developed a domestic-scale prototype experimental solar cooling system, which consisted of a 12 m^2 vacuum tubular solar collector, a 4.5 kW LiBr/H_2O absorption chiller, a 1000 l cold storage tank and a 6 kW fan coil. The average COP of the system was 0.58. Experimental results proved the feasibility of the concept of cold store at this scale, with chilled water temperatures as low as 7.4 °C, demonstrating its potential use in cooling domestic scale buildings.

The existing experimental results showed that solar-powered single-effect absorption cooling systems were capable of working in the driving temperature range of 65–100 °C. Table 1 summarized the main operating parameters of the existing solar cooling systems. Generally, the system COP of about 0.6 could be obtained under the design condition. However, when a chiller worked at partial load, a low efficiency from solar to cooling would be obtained. Rodríguez Hidalgo et al. [8] developed an experimental facility with 50 m^2 flat-plate solar collectors. It fed a 35 kW single-effect LiBr/H_2O absorption machine. Because the chiller worked at partial load, the seasonal value for COP during the already specified 2004 summer season was concluded to be 0.33. Therefore, it is important to select the adequate size of the absorption machine, to make it work at nominal operating conditions, so that the system COP reaches the nominal value and solar fraction, consequently, is higher.

2.2. Theoretical analysis and simulation

The main components of a solar absorption cooling system are the solar field, the absorption chiller and the heat storage water tank. The overall system performances depend on the coupling of these three components. Such research works were carried out mainly by theoretical analysis and simulation with the aid of TRNSYS program.

Balghouthi et al. [16] presented a research project aiming at assessing the feasibility of solar-powered absorption cooling technology under Tunisian conditions. The system was modeled using the TRNSYS and EES programs with a meteorological year data file containing the weather parameters of Tunis, the capital of Tunisia. The optimized system for a typical building of 150 m^2 was composed of a LiBr/H_2O absorption chiller of a capacity of 11 kW, a 30 m^2 flat-plate solar collector area tilted 35° from the horizontal and a 0.8 m^3 hot water storage tank.

Florides et al. [17] designed a LiBr/H_2O absorption unit with the cooling capacity of 11 kW, which could cover the cooling load of a typical model house in Cyprus. The optimum system as obtained from the complete system simulations consisted of 15 m^2 compound parabolic collectors tilted at 30° from horizontal and a 600 l hot water storage tank.

Assilzadeh et al. [18] reported a solar cooling system that had been designed for Malaysia and similar tropical regions using evacuated tubular solar collectors and a $LiBr/H_2O$ absorption unit. It was shown that a 0.8 m^3 hot water storage tank was essential in order to achieve continuous operation and increase the reliability of the system. The optimum system for Malaysia's climate for a 3.5 kW system consisted of 35 m^2 evacuated tubular solar collector sloped at 20°.

Atmaca and Yigit [19] simulated a solar cooling system based on a 10.5 kW constant cooling load. A modular computer program was developed for the absorption system to simulate various cycle configurations and solar energy parameters for Antalya, Turkey. It was shown that the solar collector area of 50 m^2, a 3750 kg storage tank mass seemed to be the best choice.

Joudi and Abdul-Ghafour [20] developed an integrated program for the complete simulation of a solar cooling system with a $LiBr/H_2O$ absorption chiller. The results obtained from the simulation were used to develop a general design procedure for solar cooling systems, presented in a graphical form called the cooling f-chart. Using this design chart could simplify the designer's task for predicting the long term cooling energy supplied from a solar collector array serving an absorption chilled water system. Besides, a correlation was developed from the simulation results for estimating the hot water storage size necessary for the solar cooling system.

The coupling of the main components of a solar cooling system is determined by the cooling demand time series, solar resource availability, climatic conditions, component cost and component performance characteristics. The optimum design should be based upon simulation results according to practical projects. However, as a rule of thumb, the specific cooling capacity (the specific cooling capacity is defined as the cooling capacity of a solar cooling system per unit of solar collector area) was observed to be 0.1–0.7 kW/m^2. Besides, the specific tank volume (the specific tank volume is defined as the heat storage tank volume of a solar cooling system per unit of solar collector area) was deduced to be 0.01–0.08 m^3/m^2.

2.3. New design options of solar-powered single-effect absorption cooling systems

2.3.1. Solar collectors

Nearly all solar cooling systems were driven by ordinary flat-plate or evacuated tubular solar collectors, which are available in the market. However, some new types of solar collectors have also been taken into account.

Mazloumi et al. [21] simulated a single-effect absorption cooling system designed to supply the cooling load of a typical house in Ahwaz where the cooling load peak was about 17.5 kW. Solar energy was absorbed by a horizontal N-S parabolic trough collector and stored in an insulated thermal storage tank. It was concluded that the minimum required collector area was about 57.6 m^2, which could supply the cooling loads for the sunshine hours of the design day.

It was said that solar absorption systems required a large area of stationary collectors such as flat-plate or evacuated tubular solar collectors to cool residential places with low cooling loads; consequently, the use of these collectors could be impractical to cool places with high amounts of cooling load. The parabolic trough collectors obtained more solar heat energy in the areas with suitable direct radiation, which caused the cooling systems to operate earlier. Besides, the operation of such solar cooling systems could be considered after sunset by the storage of solar energy. In comparison, the operation of those powered by stationary collectors was commonly considered from sunrise to sunset [21].

Concentrating photovoltaic (CPV) systems can operate at higher temperatures than flat-plate collectors. Collecting the rejected heat from a CPV system leads to a CPV/thermal (CPVT) system, providing both electricity and heat at medium rather than low temperatures. CPVT collectors may operate at temperatures above 100 °C, and the thermal energy can drive processes such as refrigeration, desalination and steam production. In the CPVT system, the thermal energy is a low cost byproduct and, therefore, could lead to a much more competitive solar cooling solution [22].

Mittelman et al. [22] investigated the performance and cost of a CPVT system with single-effect absorption cooling. The results showed that under a wide range of economic conditions, the combined solar cooling and power generation plant could be comparable to, and sometimes even significantly better than, the conventional alternative. This is in contrast with solar cooling based on thermal collectors, which is usually found to be significantly more expensive than conventional cooling.

2.3.2. Auxiliary energy systems

For the purpose of all-weather operation, it is necessary to install auxiliary energy systems to supplement solar-powered cooling systems. Generally speaking, apart from electric heaters and oil boilers, almost all the auxiliary energy-to be used in case of scarce solar irradiation is supplied by a gas fired auxiliary boiler. However, such arrangement implies a low energy efficiency, since the combination of the gas fired heater and the single stage absorption chiller is largely less efficient than a traditional electric-driven compression system. In fact, the former usually uses around 1.7 kWh of primary energy to produce 1 kWh of cooling energy, whereas the latter only needs 0.7 kWh. Thus, the use of a gas-fired heater can be acceptable only when the auxiliary energy to be supplied is low [23]. Such a conclusion was also drawn by Calise et al. [24]. Compared with the auxiliary energy system of a gas-fired heater, the layout of an electric water-cooled chiller showed better energetic performance. It was showed that the primary energy saving of such a system vs. a traditional electric heat pump was close to 37% [24].

In addition, the auxiliary energy systems for solar cooling systems could be used with other options of clean energy or renewable energy. Pongtornkulpanich et al. [25] designed a solar-driven 10-ton $LiBr/H_2O$ single-effect absorption cooling system. It was shown that the 72 m^2 evacuated tube solar collector delivered a yearly average 81% of the thermal energy required by the chiller, with the remaining 19% generated by a LPG-fired backup heating unit.

Prasartkaew and Kumar [26] presented a solar-biomass hybrid absorption cooling system which was suitable for residential applications. It consisted of three main parts: solar water heating with a storage tank, biomass gasifier fired hot water boiler, and single-effect absorption chiller. The biomass gasifier hot water boiler was located between the hot water storage tank and absorption chiller machine. This insulated boiler had two functions: it worked as an auxiliary boiler when solar energy was not enough and worked as main heat source when the solar radiation was not available. Based upon the Bangkok meteorological data, the COP of the chiller and the overall system was found to be 0.7 and 0.55, respectively. Besides, the biomass (charcoal) consumption for 24 h operation was 24.44 kg/day. The solar-biomass hybrid air conditioning showed great potential for the residential building comfort and the reduction of green house gas emissions.

Ahmed Hamza et al. [27] reported the performance of an integrated cooling plant including both free cooling system and solar powered single-effect $LiBr/H_2O$ absorption chiller, which had been in operation since August 2002 in Oberhausen, Germany. A floor space of 270 m^2 was air-conditioned by the plant. The plant included 35.17 kW cooling absorption chiller, vacuum tube collectors' aperture area of 108 m^2, hot water storage capacity of 6.8 m^3, cold water storage capacity of 1.5 m^3 and a 134 kW cooling tower. It was shown that free cooling in some cooling months could be up to 70% while it was about 25% during the 5 years period of the

plant operation. For sunny clear sky days, collectors' field efficiency ranged from 0.352 to 0.492 and chiller COP varied from 0.37 to 0.81, respectively.

Li et al. [28] designed a 200 kW solar absorption cooling system assisted by a ground source heat pump (GSHP) with a rated cooling capacity of 391 kW. The chilled water produced by the solar cooling system was stored in a cold storage water tank. In order to maintain the setting temperature inside the cold storage water tank, the ground source heat pump was turned on either when the water temperature was higher than 18 °C or during the period from 22:00 to 7:00 with cheaper electricity tariff.

As for a solar cooling system without any backup system, Marc et al. [29] indicated that it was very difficult to design this kind of installation and particularly to define the appropriate refrigerating capacity of the chiller. In a case where the chiller is undersized and runs in nominal conditions with good performances, thermal comfort inside the building will not be achieved in some critical periods of the year. In a second case where the chiller is oversized and does not run in nominal conditions with low performances, thermal comfort inside the building is achieved.

2.3.3. Cooling modes

Although the COP would be higher with a wet cooling tower, a dry cooling tower could be selected in order to avoid the usual problem of the legionella of the wet cooling towers. Monné et al. [30] reported a solar cooling system which consisted of 37.5 m^2 of flat-plate collectors, a 4.5 kW single-effect $LiBr/H_2O$ absorption chiller and a dry cooling tower. The performance analysis of the solar driven chiller showed the average values of COP close to 0.6 in 2007 and between 0.46 and 0.56 in 2008. Concerning to the average cooling power, the chiller reached values between 4.0 and 5.6 kW in 2007 and between 3.6 and 5.3 kW in 2008. The studies indicated the great influence of the temperature of the heat rejection sink on the machine performance. In order to improve the performance of the absorption chiller, a geothermal system was proposed. It was shown that with the geothermal cooling system, the COP of the chiller could be improved up to 42% over than that of the air-cooled one.

Helm et al. [31] suggested that a low temperature latent heat storage together with a dry air cooler in solar-driven absorption cooling systems was a promising alternative to a conventional wet cooling tower. The reject heat of the absorption chiller was buffered by the heat storage and transferred to the ambient during periods of low ambient temperatures, e.g. night time or off-peak situations. Especially in low capacity applications, the absence of a wet cooling tower substantially facilitated the introduction of absorption technology. An analysis of the thermal design of the different system components showed that a latent heat storage allowed for moderate temperatures of the driving heat and thus substantially reduced the over-sizing of the solar collector system arising from the application of dry air cooling as compared to a standard system design with wet cooling tower. In this study, the phase-change material (PCM) calcium chloride hexahydrate with phase transition, i.e. melting and solidification, in the temperature range of 27–29 °C was applied. The latent heat storage provided a 10 times higher volumetric storage density in comparison to a conventional water heat storage.

By means of a latent heat storage integrated into the heat rejection loop of the chiller, a part of the auxiliary power demand can be shifted to off-peak hours with only a marginal increase of the overall electric consumption of the solar cooling system. As a consequence, a reduction of the operating cost is accomplished due to the reduced night tariff for electricity. And for the operation of the electric grid, a more even load profile with reduced daytime peaks is achieved, allowing for increased efficiency and reduced cost in power generation [31].

3. Solar-powered cooling systems based on other absorption chillers

3.1. Solar-powered double-effect absorption cooling systems

Development in gas-fired absorption systems in recent years, for $LiBr/H_2O$ chillers, have made available in the market double-effect systems with COP 1.1–1.2. These systems may be adapted to and employed in a solar-powered installation with high-temperature solar collectors. Qu et al. [32] installed a solar-powered double-effect absorption cooling system at Carnegie Mellon University. The system incorporated 52 m^2 of linear parabolic trough solar collectors; a 16 kW double-effect, $LiBr/H_2O$ absorption chiller, and a heat recovery heat exchanger with their circulation pumps and control valves. The absorption chiller installed was a dual fired, double-effect, $LiBr/H_2O$ chiller integrated with a cooling tower. It had a natural gas burner in its regenerator to provide heat when solar energy was inadequate. Till now, only this system of the kind has been successfully operated for more than one year.

According to the experiments under typical weather condition of Pittsburgh in summer, the overall solar efficiency of the parabolic trough solar collectors was approximately 33–40% when the heat transfer fluid was operated at 150–160 °C. The COP of the installed absorption chiller was in the range 1.0–1.1. The solar COP of the overall installed solar cooling system, the product of the COP of absorption chiller and the solar collector efficiency, was therefore about 0.33–0.44. The maximum output of the absorption chiller was 12 kW. The reason for this capacity, lower than the chillers design capacity of 16 kW, was mainly related to the intensity of direct solar radiation. Due to the relative high humidity of Pittsburgh in summer, the direct solar radiation was relative low with typical values of 600–850 W/m^2.

3.2. Solar-powered half-effect absorption cooling systems

Kim and Infante Ferreira [33] carried out the simulations of various absorption cycles under solar cooling conditions and concluded that a half-effect $LiBr/H_2O$ cycle would be most promising for air-cooled solar absorption air conditioning in terms of initial solar collector cost, which was attributable to the excellent thermodynamic properties of the working fluids and the low driving temperature requirement of the half-effect absorption cycle. They also theoretically investigated a particular type of half-effect air-cooled $LiBr/H_2O$ absorption chiller which could work effectively in an extremely hot climate with little risk of crystallization. The chiller could be cooled by both directly and indirectly air-cooled operating mode. It was concluded that the direct and indirect air-cooled chillers were able to deliver chilled water at 5.7 °C and 7.8 °C with a COP of 0.38 and 0.36, respectively, from 90 °C hot water under 35 °C ambient temperature condition. At 50 °C ambient temperature, the COP and cooling power of the direct air-cooled chiller were reduced to 81.6% and 37.5% of those at 35 °C and the reductions were greater for the indirect air-cooled chiller being 75% and 35.6%, respectively.

Moreover, risks of LiBr crystallization in the chillers were less than that of a commercial water-cooled machine for hot water temperature up to 100 °C and ambient temperature up to 50 °C when chilled water return temperature was maintained at 13 °C. The effective operability in extremely hot weather conditions and the reduced risk of crystallization made the chillers considered in this study particularly suitable for air-cooled solar absorption cooling systems in hot and dry regions where a closed system is preferred due to the scarcity of water.

3.3. Solar-powered two-stage absorption cooling systems

For the purpose of taking advantage of low grade heat with temperatures lower than 90 °C at high condensation temperatures, advanced multistage absorption cycles could be adopted. These cycles have lower COPs than standard ones but allow operation with generation and condensation temperatures within the indicated limits [34]. Izquierdo et al. [34] studied a double stage air/water cooled $LiBr/H_2O$ cycle evaporating at 5 °C and fed by solar energy from flat-plate collectors. It was observed that the use of double-stage systems permitted the use of condensation temperatures 13 °C higher than those suitable for single-stage ones. Double-stage absorption cycles avoided crystallization occurrence inside the absorption machine until condensation temperatures equaled to 53 °C. It was also shown that about 80 °C of generation temperature were required in the double-stage absorption machine when condensation temperature reached 50 °C, obtaining a COP of 0.38 in the theoretical cycle.

Further studies on this cycle indicated that the entropy generated and the exergy destroyed by the air cooled system were higher than the entropy generated and the exergy destroyed by the water cooled one. The difference between the values increased as the absorption temperature increased. For an absorption temperature equal to 50 °C, the air cooled mode generated 14% more entropy and destroyed 14% more exergy than the water cooled one. In addition, the exergetic efficiency of the double stage cycle considered was lower than that of the single and double effect cycles because it worked with heat at lower temperature. The double stage system had about 22% less exergetic efficiency than the single effect one and 32% less exergetic efficiency than the double effect one [35].

4. Conclusions and suggestions

Solar cooling systems can be used, either as stand-alone systems or with conventional air-conditioning systems, to improve the indoor air quality of all types of buildings. In order to increase the utilization ratio and solar fraction, nearly all solar cooling systems are multifunctional and are used to supply heating and hot water in other seasons. It is concluded that solar cooling projects contain various categories, such as office buildings, residential buildings, schools, hospitals and laboratories. They have shown great potential in the energy conservation of air-conditioning systems in civil buildings. Taking southern European and Mediterranean areas for example, solar cooling systems could lead to primary energy savings in the range of 40–50% [4]. However, solar cooling technology is still in an early stage of development. Besides, the existing research works are mainly based on civil buildings. A lot of research work is still needed to be done for large-scale applications in industrial buildings [36].

It is concluded that two very influential parameters determine the most economical solar cooling option; the cost of the solar collection technologies and the performance of the refrigeration technologies. Besides, solar resource availability is another important factor in determining the most suitable solar cooling technology for a certain location. In addition to the amount of annual solar yield (direct normal irradiation or global irradiation on a horizontal surface), the distribution of global irradiation used by non-concentrating technologies may be completely different from the distribution of direct irradiation used by concentrating technologies, depending on the location [37]. Currently, corresponding to the flat-plate and evacuated tubular solar collectors available in the market, most of the solar cooling systems are based mainly on single-effect absorption chillers, a proven technology employing $LiBr/H_2O$ as the working fluid pair. The developments in gas-fired systems of this type make available double-effect chillers with considerably higher COP than their single-effect counterparts, which makes it possible to reduce the amount of solar heat required per kW of cooling [38]. These systems require, however, high-temperature solar collectors. At current prices, the high COP, high temperature alternative is still more costly than the low temperature one. Nevertheless, for the buildings with high amounts of cooling load and limited installation area, solar-powered double-effect absorption cooling systems may be considered on condition that the direct irradiation is high enough. As for half-effect absorption chillers and two-stage absorption chillers, although they can also be driven by ordinary flat-plate or evacuated tubular solar collectors, the COPs of such chillers are somewhat low, which range between 0.3 and 0.4. They seem to be only competitive when using air cooled mode. Owing to their effective operation at high condensation temperatures up to 50 °C without the risk of crystallization, they are more suitable for air-cooled solar absorption cooling systems in hot and dry regions which are short of water.

Based upon the research work of solar-powered single-effect absorption cooling systems, some suggestions are given as follows.

Being the leading products in the market, the flat-plate and evacuated tubular solar collectors are still the major choices for solar absorption cooling systems in the near future. However, with the further development of CPVT technology, the combined solar cooling and power generation plants based upon CPVT systems and single-effect absorption chillers may be more competitive in both economic and technological aspects.

The auxiliary energy systems of solar cooling systems are recommended to be other renewable energy or high-efficiency heat pumps. With the spread and exploitation of ground source heat pump technology, high-efficiency ground source heat pump systems may be the suitable choices for the auxiliary energy of solar cooling systems. But when the solar cooling systems are used to undertake partial cooling load in large and medium buildings, they are always integrated with conventional air/water cooled air-conditioning systems. Under such circumstances, it is better to directly use these conventional cooling systems as the auxiliary energy systems, which makes the whole integrated cooling systems simpler and easier to be controlled. Furthermore, it is highly suggested to establish optimal operational control strategy so as to realize smooth switch between the solar cooling system and the auxiliary energy system.

With regard to cooling mode, ground cooling may be applied in some cases to eliminate the need for cooling towers. A higher system COP may thus be obtained owing to the fact that the ground temperature is always lower than the water temperature from a cooling tower. In addition, solar cooling systems are more complicated compared to conventional air-conditioning systems, which has a negative effect on their applications especially for buildings with low cooling load. Hence, the air-cooled absorption chillers have potential to be used in minitype solar cooling systems, such as those in residential buildings.

According to the existing research work, solar cooling systems always include the heat storage water tanks which accumulate heat by solar collecting circulation. On the whole, the specific tank volume was concluded to be 0.01–0.08 m^3/m^2. As for solar cooling systems only operating in cooling mode, such as those in tropical areas, the lower values of the specific tank volume are suggested to be used. However, the majority of solar cooling systems are integrated energy systems which including heating, cooling and hot water supplying. In such cases, the higher values of the specific tank volume should be adopted. A potential alternative for thermal storage may be PCM materials, which have higher volumetric storage density compared to conventional water heat storage.

Anyway, although there are some research results and new design options as shown in Table 2, which can be used for reference, almost no standardised design guidelines exit. The main obstacles for large scale application of solar cooling systems, beside the high

Table 2
Conventional and new design options of solar-powered single-effect absorption cooling systems.

Subsystem	Conventional methods	New design options
Solar collectors	Flat-plate or evacuated tubular solar collector	Parabolic trough collector and CPVT
Auxiliary energy systems	Electric heater, oil/gas boiler and conventional air/water cooled cooling system	LPG-fired heating unit, biomass gasifier boiler, free cooling system and GSHP
Cooling modes	Water-cooled mode using a cooling tower	Air-cooled, ground cooling and PCM together with an air cooler
Heat storage modes	Heat storage water tank	PCM

first cost, are the lack of practical experience and acquaintance among architects, builders and planners with the design, control and operation of these systems [4]. Thereby, it is highly recommended to carry out such research works according to different areas. In China, the technical code for solar air conditioning system of civil buildings has been completed and will be published in the near future.

Finally, it is indicated that solar cooling systems would not be competitive compared with standard cooling systems at present energy prices. The technology of solar cooling is not presently economically feasible without subsidy, mainly because of its high investment cost. Assuming that solar cooling technology could obtain the same amount of subsidies and incentives as solar PV and water heating systems, the optimized solar cooling system would have a payback period of 13.8 years, which was 40% less than the case without government subsidies [39]. Similar conclusions were also derived by Desideri et al. [40]. Therefore, there is a strong need both for some kind of investment incentive and also for energy tax that would help to reflect the full environmental costs of conventional fuels.

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